

Nuclear constraints on gravitational waves from rapidly rotating neutron stars

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(Dated: December 2, 2008)

Abstract

Gravitational waves are tiny disturbances in space-time and are a fundamental, although not yet directly confirmed, prediction of General Relativity. Rapidly rotating neutron stars are one of the possible sources of gravitational radiation dependent upon pulsar's rotational frequency, details of the equation of state of stellar matter, and distance to detector. Applying an equation of state with symmetry energy constrained by recent nuclear laboratory data, we set an upper limit on the strain-amplitude of gravitational waves emitted by rapidly rotating neutron stars.

PACS numbers: 04.30.-w, 97.60.Gb, 97.60.Jd, 21.65.Mn

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I. INTRODUCTION

General relativity is a theory of gravitation consistent with special relativity, and in particular with its fundamental principle that nothing can travel faster than light. This means that any change in the gravitational field is not felt instantaneously everywhere in space – it needs some time to propagate. In general relativity such disturbances travel at exactly the same speed as electromagnetic waves in vacuum and are named *gravitational waves*. In this sense gravitational waves could be regarded as the gravitational equivalent of electromagnetic radiation – just as electromagnetic waves carry information about rearrangement of electric charges and currents, gravitational waves carry similar information about rearrangement of masses in space.

Although a fundamental prediction of general relativity, gravitational waves are yet to be detected directly. Such an observation would have profound consequences for our basic understanding of matter, space and time, and how they couple to each other. Because gravity interacts extremely weakly with matter, gravitational waves would provide detailed information about their sources presently hidden, or dark, to current electromagnetic observations [1, 2]. Due to their potential as a unique probe of new physics and their fundamental nature, the search for gravitational waves has attracted enormous effort over the last few years by the LIGO [3], VIRGO (e.g., Ref. [4]), and GEO (e.g., Ref. [5]) collaborations. Moreover, LISA (the Laser Interferometric Space Antenna) is currently being jointly designed by NASA in the United States and ESA (the European Space Agency), and is scheduled to be launched into orbit around 2018 providing an unprecedented instrument for gravitational waves search and detection [2].

Rapidly rotating neutron stars could be one of the major candidates for sources of continuous gravitational radiation in the frequency bandwidth of ground-based laser interferometric detectors such as LIGO and VIRGO. To emit gravitational waves over extended period of time, a rotating object bound by gravity must have some kind of long-living axial asymmetry [6]. In the literature several possible mechanism leading to such deformations have been proposed (e.g., Ref.[6]). Among the factors contributing to axial asymmetries, relevant to our present study, is the anisotropic stress which may accumulate during the crystallization period of the neutron star crust and thus support axial distortions [7]. On the other hand, gravitational wave strain amplitude depends on the degree to which the neutron star is de-

formed from axial asymmetry, which, in turn, is dependent upon the details of the equation of state (EOS) of neutron-rich stellar matter. Presently, the EOS of dense, neutron-rich matter is still rather uncertain mainly due to the poorly known density dependence of the nuclear symmetry energy $E_{\text{sym}}(\rho)$, e.g. [12]. Heavy-ion reactions with radioactive beams could provide unique means to constrain the uncertain density behavior of the nuclear symmetry energy and thus the EOS of neutron-rich nuclear matter, e.g. [13, 14, 15, 16, 17]. Although there are important differences between dense, neutron-rich matter produced in the laboratory and that found in the interior of neutron stars, it is still very useful and insightful to study the astrophysical implications of the constrained EOS – in particular, its impact on the neutron star properties and the resultant gravitational waves. Following a recent work [11] in which we have constrained the gravitational waves expected from elliptically deformed *slowly rotating* pulsars, in this paper we extend our studies to *rapidly rotating* neutron stars. Applying several nucleonic EOSs, we calculate the strain amplitude of gravitational waves expected from the fastest neutron stars known as of today. Particular attention is paid to predictions with an EOS with symmetry energy constrained by very recent nuclear laboratory data. These results set an upper limit on the strain amplitude of gravitational radiation expected from rapidly rotating neutron stars. This paper is organized in the following manner. After the introductory remarks in this section, in the next section we discuss briefly the formalism for calculating the gravitational wave strain amplitude for rapidly rotating neutron stars. Our results are presented and discussed in section 3. We conclude in section 4 with a short summary.

II. FORMALISM

In what follows we review briefly the formalism used to calculate the gravitational wave strain amplitude. Here we are specifically concerned with gravitational waves (GWs) from rapidly rotating neutron stars. (Details about computing the strain amplitude in the case of slowly rotating pulsars can be found in Ref. [11] and references therein.) A spinning neutron star is expected to emit GWs if it is not perfectly symmetric about its rotational axis. As already mentioned, non-axial asymmetries may be produced through several mechanisms such as elastic deformations of the solid crust or core or distortion of the whole star by extremely strong misaligned magnetic fields [18]. Such processes generally result in a triaxial

neutron star configuration [3] which, in the quadrupole approximation and with rotation and angular momentum axes aligned, would cause gravitational waves at *twice* the star's rotational frequency [3]. These waves have characteristic strain amplitude at the Earth's vicinity (assuming an optimal orientation of the rotation axis with respect to the observer) of [19]

$$h_0 = \frac{16\pi^2 G}{c^4} \frac{\epsilon I_{zz} \nu^2}{r}, \quad (1)$$

where ν is the neutron star rotational frequency, I_{zz} its principal moment of inertia, $\epsilon = (I_{xx} - I_{yy})/I_{zz}$ its equatorial ellipticity, and r its distance to Earth.

Provided the spin-down rate, $\dot{\nu}$, for a given pulsar is known, h_0 could be written as [20]

$$h_0^{sd} = \frac{5}{2} \left(\frac{G I_{zz} |\dot{\nu}|}{c^3 r^2 \nu} \right)^{1/2}, \quad (2)$$

which provides an alternative way for calculating the gravitational wave strain amplitude. Here we should mention that in such calculations one assumes that the *only* mechanism contributing to the pulsar's observed spin-down is gravitational radiation. However, other mechanisms could also account for the star's observed decrease in rotational frequency such as magnetic dipole radiation, and particle acceleration in the magnetosphere [21]. Despite these uncertainties, calculations of gravitational wave strain amplitude through Eq. (2) are still important because, in addition to providing a rather conservative upper limit on the expected gravitational radiation, they also serve to estimate another very uncertain but important quantity – the ellipticity ϵ , which is a measure of the neutron star deformation. (ϵ could be evaluated through combining Eqs. (1) and (2).) Provided one knows the exact rotational frequency, principal moment of inertia, distance to detector, and ellipticity (or spin-down rate), Eq. (1) (or Eq. (2)) can be used to calculate the gravitational wave strain amplitude. These estimates are then to be compared with the current upper limits for sensitivity of the laser interferometric observatories (e.g., LIGO). In the present work we use the RNS code [43], written and made available to the public by Nikolaos Stergioulas, to calculate the principal moment of inertia (and other properties) of rapidly rotating neutron stars. (The *RNS* code is available as a public domain program at <http://www.gravity.phys.uwm.edu/rns/>.)

Here we should point out that the fastest pulsars presently known (PSR B1937+21, PSR J1748-2446ad, and XTE J1739-285) have rotational frequencies in the upper end of the current detection limit of LIGO ($\sim 200 Hz$). On the other hand, Eq. (1) implies that *rapidly*

rotating neutron stars emit stronger gravitational waves, and therefore it is important to study the gravitational waves expected from such neutron stars.

III. RESULTS AND DISCUSSION

In this work, we calculate the gravitational wave strain amplitude h_0 for the fastest pulsars currently known employing several nucleonic equations of state. We assume a simple model

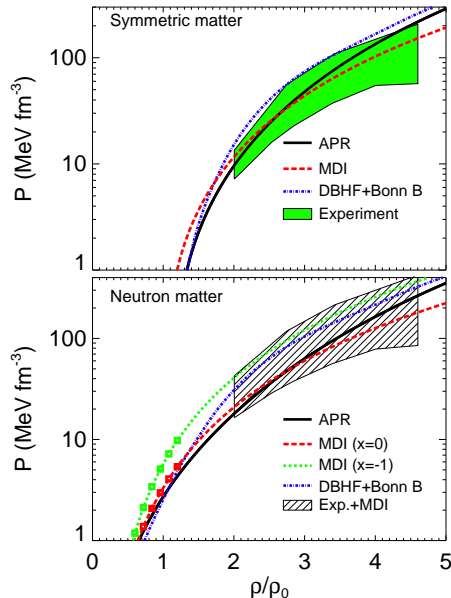


FIG. 1: (Color online) Pressure as a function of density for symmetric (upper panel) and pure neutron (lower panel) matter. Taken from Ref. [11]. (Details about the figure can be found in Ref. [11].)

TABLE I: Properties of the *rapidly rotating* pulsars considered in this study. The first column identifies the pulsar. The remaining columns exhibit the following quantities: rotational frequency; first derivative of the rotational frequency; distance to Earth; corresponding reference.

Pulsar	$\nu(Hz)$	$\dot{\nu}(Hz\ s^{-1})$	$r(kpc)$	Reference
PSR B1937+21	641.93	-4.33×10^{-14}	3.60	[38, 39]
PSR J1748-2446ad	716.35	—	8.70	[40, 41]
XTE J1739-285	1122.00	—	10.60	[42]

of stellar matter of nucleons and light leptons (electrons and muons) in beta-equilibrium. Details about the constrained equation of state calculated with the Momentum Dependent Interaction (MDI) [22] applied in the present paper can be found, for instance, in Refs. [11, 17]. Here we recall briefly its main features. For many astrophysical studies (as those in this paper), it is more convenient to express the EOS in terms of the pressure as a function of density and isospin asymmetry. In Fig. 1 we show pressure as a function of density for symmetric (upper panel) and pure neutron matter (lower panel). The EOS of symmetric nuclear matter with the MDI interaction is constrained by the available data on collective flow in relativistic heavy-ion collisions. The parameter x is introduced in the single-particle potential of the MDI EOS to account for the largely uncertain density dependence of the nuclear symmetry energy $E_{sym}(\rho)$ as predicted by various many-body frameworks and models of the nuclear force. Since it was demonstrated by Li and Chen [23] and Li and Steiner [24] that only equations of state with x in the range between -1 and 0 have symmetry energy consistent with the isospin-diffusion laboratory data and measurements of the skin thickness of ^{208}Pb , we therefore consider only these two limiting cases in calculating boundaries of the possible (rotating) neutron star configurations. It is also important to mention that the symmetry energy extracted very recently from isoscaling analysis of heavy-ion reactions is consistent with the MDI calculation of the EOS with $x = 0$ [25]. The MDI EOS has been applied to constrain the neutron star radius [24] with a suggested range compatible with the best estimates from observations. It has been also used to constrain a possible time variation of the gravitational constant G [8] via the *gravitochemical heating* approach developed by Jofre et al. [26]. More recently we applied the MDI EOS to constrain the global properties of (rapidly) rotating neutron stars [9, 10] and the strain amplitude of the gravitational waves expected from elliptically deformed *slowly rotating* pulsars [11]. In addition to the MDI EOS, in Fig. 1 we show results by Akmal et al. [27] with the $A18 + \delta v + UIX^*$ interaction (APR) and very recent Dirac-Brueckner-Hartree-Fock (DBHF) calculations [28] with Bonn B One-Boson-Exchange (OBE) potential (DBHF+Bonn B) [31]. (Older calculations of the DBHF+Bonn B EOS can be found in [29, 30].) Below the baryon density of approximately 0.07 fm^{-3} the equations of state applied here are supplemented by a crustal EOS, which is more suitable for the low density regime. Namely, we apply the EOS by Pethick et al. [32] for the inner crust and the one by Haensel and Pichon [33] for the outer crust. At the highest densities we assume a continuous functional for the EOSs

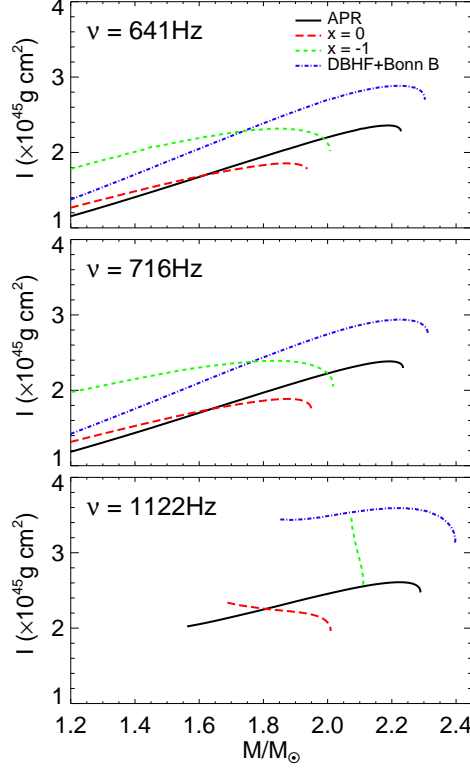


FIG. 2: (Color online) Neutron star moment of inertia as a function of stellar mass. Results are partially taken from Ref. [10].

employed in this work.

In this paper we study gravitational waves emitted from rapidly rotating neutron stars. Specifically, we examine configurations rotating at 641, 716, and 1122 Hz. These frequencies represent the three fastest pulsars discovered as of today. The properties of these neutron stars (of interest in this study) are summarized in Table 1. In Fig. 3 we show the neutron star moment of inertia as a function of stellar mass. The upper panel shows the moment of inertia of PSR B1937+21, while the middle and lower panels display the moments of inertia of PSR J1748-2446ad and XTE J1739-285 respectively. As already observed previously, the moment of inertia increases with rotational frequency, while the range of possible neutron star configurations decreases (see, for instance, Refs. [9, 10]).

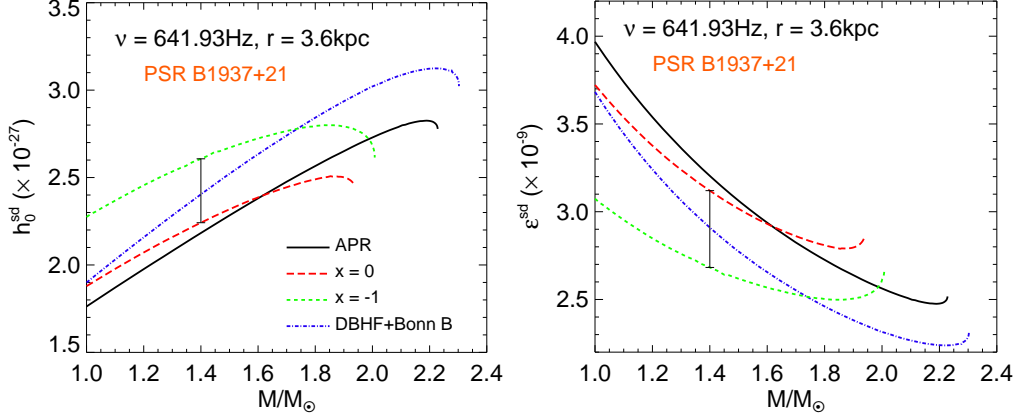


FIG. 3: (Color online) Neutron star gravitational wave strain amplitude (left panel) and ellipticity (right panel) as a function of stellar mass. For computing h_0^{sd} Eq. (2) has been used. The ellipticity, ϵ^{sd} , has been calculated by combining Eqs. (1) and (2). The error bars between the $x = 0$ and $x = -1$ EOSs, in both frames, provide a limit on the strain amplitude of the gravitational waves to be expected from this neutron star and its ellipticity, and show a specific case for stellar models of $1.4M_{\odot}$.

A. Rotations at 641 Hz

In this subsection we study gravitational waves from neutron star models rotating a 641 Hz [38], which was the rotational frequency of the fastest pulsar (PSR B1937+21) for 23 years before the discovery by Hessels et al. [40] in 2006. Since its first observation in 1982, this pulsar has been studied extensively and an observed spin-down rate has been measured (see Table 1). Using the spin-down rate, we placed an upper limit on the gravitational wave strain amplitude from PSR B1937+21, assuming the only mechanism contributing to the observed spin-down is gravitational radiation. This is a rather simplistic approach because, as already mentioned, there are other mechanisms that could/would account for the star's observed decrease in rotational frequency. For instance, young pulsars could exhibit significant amount of energy loss through electromagnetic processes. Nevertheless, this method still provides a conservative upper bound to the amplitude of the GWs that can be emitted. The spin-down rate corresponds to a loss in kinetic energy at a rate of $\dot{E} = 4\pi^2 I_{zz} \nu |\dot{\nu}| \sim [0.6 - 3.1] \times 10^{36} \text{ erg/s}$, depending on the EOS. Assuming that the full amount of this energy loss is being radiated away is in the form of gravitational radiation, the gravitational wave strain amplitude can be calculated through Eq. (2). Similar calculations

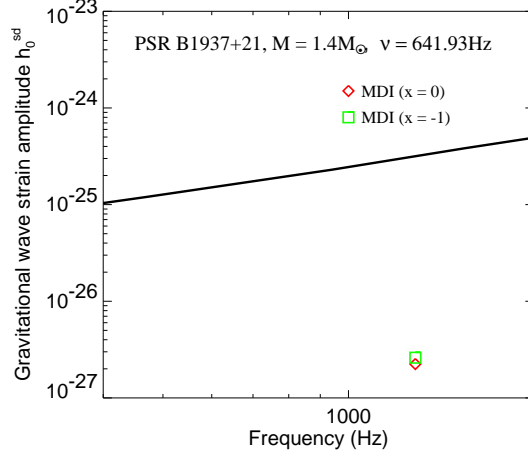


FIG. 4: (Color online) Gravitational wave strain amplitude as a function of the gravitational wave frequency. The characters denote the strain amplitude of the GWs expected to be emitted from neutron stars spinning at 641.93Hz with mass $1.4M_{\odot}$. Solid line (adapted from Ref. [3]) denotes the current upper limit of the LIGO sensitivity.

for this pulsar and others with an observed spin-down rate have been done in the past [3, 20]. However, such calculations simply used the “fiducial” value of $10^{45}g\text{ cm}^2$ for the moment of inertia I_{zz} , while here we calculate the moment of inertia of PSR B1937+21 numerically with the RNS code for each EOS (upper panel of Fig. 2).

The gravitational wave strain amplitude of PSR B1937+21 is shown in the left panel of Fig. 3. Because the MDI EOS is constrained by available nuclear laboratory data, our results with the $x = 0$ and $x = -1$ EOSs allowed us to place a rather conservative *upper* limit on the gravitational waves to be expected from this pulsar, provided the *only* mechanism accounting for its spin-down rate is gravitational radiation. Under these circumstances, the upper limit of the strain amplitude, h_0^{sd} , for neutron star models of $1.4M_{\odot}$ is in the range $h_0^{sd} = [2.24 - 2.61] \times 10^{-27}$. Similarly, we have constrained the upper limit of the ellipticity of PSR B1937+21 to be in the range $\epsilon^{sd} = [2.68 - 3.12] \times 10^{-9}$ (Fig. 3, right panel).

In Fig. 4 we take another view of the results shown in the left frame of Fig. 3. We display the maximal GW strain amplitude as a function of the GW frequency and compare our predictions with the best current detection limit of LIGO. The specific case shown is for neutron star models with mass $1.4M_{\odot}$ computed with the $x = 0$ and $x = -1$ EOSs. Since these EOSs are constrained by the available nuclear laboratory data they provide a

limit on the possible neutron star configurations and thus gravitational emission from them. From Fig. 4 it could be concluded that the GWs emitted by PSR B1937+21 associated with the pulsar's spin-down are well below the current detection limit of LIGO. On the other hand, Eq. (2), through which the GW strain amplitude has been computed, does not take into account other processes contributing to the decrease in angular velocity of the star. Moreover, Haskell et al. [35] has shown that the ellipticity of an isolated neutron star, which is a measure of stellar deformation from axial symmetry, could be as large as $\sim 10^{-6}$. This value of ϵ is 3 orders of magnitude larger than the estimates from the pulsar's spin-down shown in Fig. 3 (right panel), and would bring the GW strain amplitude within the current detection range of the interferometric detectors (e.g., LIGO). The large uncertainty of the ellipticity is dictated by the very poorly known value of the breaking strain of the neutron star crust $\bar{\sigma}_{br}$. It falls in the very wide range $\bar{\sigma}_{br} = [10^{-5} - 10^{-2}]$ and has to be pinned down from more realistic calculations. However, this is not an easy task as it requires detailed microscopic description of matter in the neutron star crust (see, e.g. Ref. [44]).

B. Rotations at 716 and 1122 Hz

In this subsection we examine the gravitational waves emitted from neutron star models rotating at 716 and 1122 Hz which are the rotational frequencies of PSR J1748-2446ad

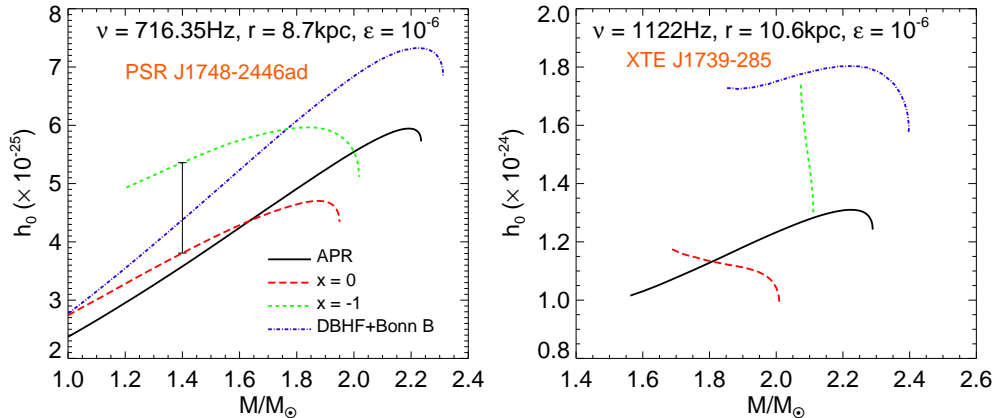


FIG. 5: (Color online) Gravitational wave strain amplitude, h_0 , versus neutron star mass for models rotating at 716 Hz (left frame) and 1122 Hz (right frame). The error bar in the left frame between the $x = 0$ and $x = -1$ EOSs provide a limit on the strain amplitude of the GWs expected from PSR J1748-2446ad and show a specific case for stellar models of $1.4M_\odot$.

and XTE J1739-285 respectively. Presently the spin-down rates of these objects are not available and therefore estimates of GW strain amplitude, and in turn ellipticity, through Eq. (2) are not possible. We calculate h_0 through Eq. (1) with I_{zz} computed with the RNS code and $\epsilon = 10^{-6}$. The specific value of ϵ chosen here maximizes h_0 and is consistent with the *largest* “mountain” expected on a isolated neutron star [35]. We show the GW strain amplitude as a function of stellar mass in Fig. 5. Because ellipticity is fixed in the present calculation, h_0 follows qualitatively the mass dependence of the moment of inertia (Fig. 2). Our results with the MDI EOS ($x = 0, -1$) set a constraint on the *upper* limit for h_0 of the GWs expected to be emitted from PSR J1748-2446ad. If the pulsar’s mass is $\sim 1.4M_\odot$ then $h_0 = [3.81 - 5.36] \times 10^{-25}$. Similarly, we have placed a limit on the strain amplitude of the GWs generated by XTE J1739-285. As previously shown [9], only narrow range of neutron star models is possible at such large frequencies (with details depending on the specific EOS of stellar matter). Moreover, the mass of XTE J1739-285 has been shown [9] to exceed the canonical value of $1.4M_\odot$. From Fig. 5 (right frame) we conclude that the *absolute upper* bound of h_0 for this neutron star is somewhere in the range $h_0 = [1.17 - 1.74] \times 10^{-24}$, if the pulsar’s mass falls in the range $M = [1.69 - 2.07]M_\odot$.

These estimates do not take into account the uncertainties in the distance measurements as well as the uncertainties in the orientation of the star with respect to Earth, and they are also regarded as upper limits as a result of the ellipticity chosen as a maximum. The results shown in Fig. 5 also reveal that h_0 depends on the EOS. However, the exact dependence could be only established, if the stellar ellipticity is also calculated consistently. Such calculations would require an exact calculation of the quadrupole moment of rapidly rotating neutron stars which is not trivial (see, e.g. Ref. [45]). Laarakkers and Poisson [45] have extended the RNS code to calculate also the quadrupole moment, Φ_{22} . The ellipticity then could be calculated as $\epsilon = (8\pi/15)^{1/2}\Phi_{22}/I_{zz}$. This would yield, however, unrealistically large values for ϵ and, in turn, h_0 (as verified in preliminary calculations).

At the end, in Fig. 6 we examine the results shown in Fig. 5 from a different perspective. We display the maximum GW strain amplitude as a function of GW frequency ($f_{gw} = 2\nu$) and compare our predictions with the best current detection limit of LIGO. As already mentioned, the ellipticity has been chosen such that to maximize h_0 . For neutron star models rotating at 716 Hz (left frame) we show specific case of stellar configurations of $1.4M_\odot$. On the other hand, in the case of rapid rotation at 1122 Hz, $1.4M_\odot$ configurations

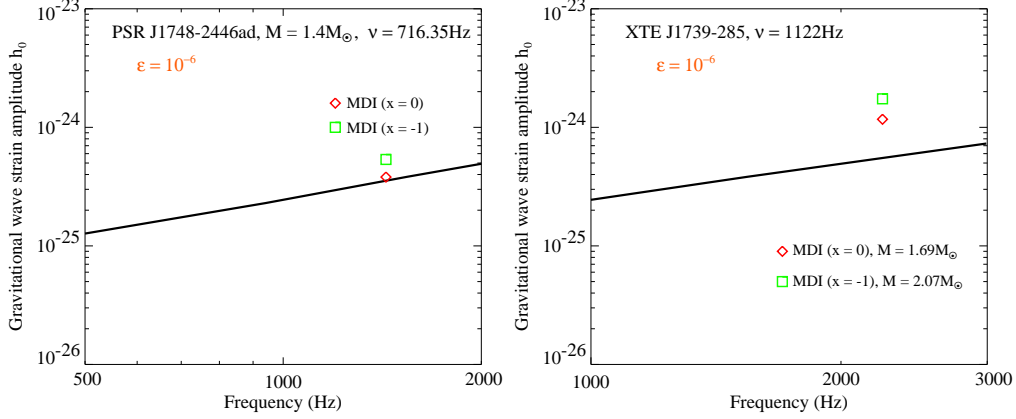


FIG. 6: (Color online) Gravitational wave strain amplitude as a function of the gravitational wave frequency for neutron star models spinning at 716 Hz (left panel) and 1122 Hz (right panel). Conventions and labelling as in Fig. 4.

do not exist as stable models should be at least $\sim 1.7M_{\odot}$ (for the $x = 0$ EOS). Therefore, in Fig. 6 (right frame) we show h_0 for the *lowest* mass neutron star models. Moreover, as recently discussed [11] low-mass neutron stars are expected to generate stronger gravitational waves (at the same rotational frequency). This is because such models are less compact (and gravitationally bound) which could result in a greater susceptibility of deformation by various mechanisms and phenomena, and ultimately lead to a stronger GW strain amplitude. The results shown in Fig. 6 would suggest that presently the gravitational radiation from these pulsars should be within the detection capabilities of LIGO. Several factors could contribute to the fact that, on the contrary, such a detection has not been made yet. First, for calculating h_0 shown in Fig. 6 we have used the maximum ellipticity $\epsilon = 10^{-6}$. On the other hand, ϵ could be significantly lower [35] which would bring h_0 to lower values and out of the LIGO's current detection range (see also the previous subsection). Second, in the present study we assume a very simple model of stellar matter consisting only beta equilibrated nucleons and light leptons (electrons and muons). On the other hand, in the core of neutron stars conditions are such that other more exotic species of particles could readily abound. Such novel phases of matter would soften considerably the EOS of stellar medium [36] leading to ultimately more compact and gravitationally tightly bound objects which could withstand larger deformation forces (and torques). Lastly, the existence of quark stars, truly exotic self-bound compact objects, is not excluded from further considerations and studies. Such stars would be able to resist huge forces (such as those resulting from extremely rapid rotation

beyond the Kepler, or mass-shedding, frequency) and as a result retain their axial symmetric shapes effectively dumping the gravitational radiation (e.g. [37]). We leave this discussion by simply recalling that Eq. (1) implies that the best possible candidates for gravitational radiation (from spinning relativistic stars) are rapidly rotating pulsars relatively close to Earth ($h_0 \sim \nu^2/r$), thus, further understanding of the neutron star's ellipticity under such rotational conditions are important for more realistic calculations.

IV. SUMMARY

In this paper we have reported predictions on the upper limit of the strain amplitude of the gravitational waves expected to be emitted from the fastest pulsars presently known. By applying an EOS with symmetry energy constrained by recent nuclear laboratory data, we obtained an upper limit on the gravitational - wave signal to be expected from PSR B1937+21, PSR J1748-2446ad, and XTE J1739-285. These predictions serve as the first direct nuclear constraint on the gravitational waves from *rapidly* rotating neutron stars.

Acknowledgements

The authors gratefully acknowledge support from the National Science Foundation under Grants No. PHY0652548 and No. PHY0757839, the Research Corporation under Award No. 7123 and the Texas Coordinating Board of Higher Education Grant No. 003565-0004-2007. We thank F. Sammarruca for providing the updated DBHF + Bonn B EOS.

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